International Journal of Plasticity 82 (2016) 127–158

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Anisotropic and asymmetrical yielding and its distorted evolution: Modeling and applications

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A R T I C L E I N F O

Article history:
Received 6 October 2015
Received in revised form 1 February 2016
Available online 19 March 2016

Keywords:
A. Yield condition
B. Anisotropic material
B. Constitutive behaviour
C. Finite elements
C. Numerical algorithms

A B S T R A C T

Characterizing the anisotropy/asymmetry-induced distortional yielding and subsequent evolution is still a challenge for potential usages of hard-to-deform materials. From perspective of multiple mechanisms, two types of yield functions are classified, viz., the principal shear stress-based models (SSM) and the stress invariants-based models (SIM); then a unified continuum-based discontinuous (CBD) framework is constructed, in which SSM and SIM are introduced to capture the distorted shape of the yielding, and an interpolation approach is adopted to smoothly present the nonlinear evolution of the distorted plasticity in the full stress space. Taking the CPB06 (Cazacu et al., 2006) and Yoon's criteria (Yoon et al., 2014) as typical SSM and SIM, the CBD framework is implemented in the explicit 3D-FE platform for practical usages by combining implicit algorithm and interpolation approach, and the Nelder-Mead (N-M) method and the genetic algorithm (GA) approach are evaluated for calibrating of CBD related to convergence, overlapping and accuracy. The evaluation proves that the GA-based method is suitable for CBD, and the SIM seems to be feasible for embedding into the CBD framework because of its solid physical basis and numerical robustness. Taking high strength titanium alloy tube (HSTT) as a case, the distorted plasticity evolution of the HSTT with six typical initial textures are characterized, then the correlations among initial textures, distorted behaviors and inhomogeneous deformation are quantitatively established to improve the multi-defect constrained formability in uniaxial tension/compression and mandrel bending.

1. Introduction

The urgent needs for lightweight and high-performance components in many industries require the precision forming of hard-to-deform materials with complex structures. The precision forming specific to these types of components depends on accurate and efficient modeling of their plastic behaviors under complex loading conditions. While coordinated by multiple mechanisms such as twinning and the Non-Schmid effect (Patra et al., 2014; Kabirian et al., 2015; Tuninetti et al., 2015), many hard-to-deform materials, not only HCP structured polycrystalline aggregates but also some BCC or even FCC structured ones, tend to present pronounced anisotropy/asymmetry behaviors. In particular, the microstructure variation during the

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http://dx.doi.org/10.1016/j.ijplas.2016.03.002
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successive deformation induces the distorted evolution of yield loci in sizes and shapes. Additionally, the forming of these components generally involves complex loadings such as tension, compression, torsion, internal pressure or their combinations. The inherent unique behaviors and external boundary conditions easily induce inhomogeneous deformation and further result in the dramatic evolution of strong texture reorientation and much distorted plasticity, which may affect the formability of these materials. Thus, to excavate the forming potentials of these high strength and lightweight materials, it is imperative and fundamental to construct suitable constitutive models to describe the distortional yielding and subsequent evolution and then to evaluate their applicability in practical processes (Gawad et al., 2015).

Based on understanding of the unique plastic behaviors such as anisotropy, to advance the constitutive modeling of newly developed materials is the ultimate frontiers (Chaboche, 2008; Banabic, 2010; Horstemeyer and Bammann, 2010; Lee and Barlat, 2014; Chang and Kochmann, 2015; Smith et al., 2015). The multi-scale modeling blueprint prevails for thoroughly characterizing the materials' constitutive features at the atomistic scope, meso scope and continuum scale (McDowell, 2010; Zhang et al., 2014). Atomistic-scale modeling is used to reveal underlying mechanisms, such as non-Schmid effects (Bassani and Racherla, 2011). Mesoscopic modeling, seen in the Taylor-Bishop-Hill polycrystal model and the Visco-plastic self-consistent (VPSC) crystal plasticity model, is used to relate the macroscale plastic deformation to the mesoscale microstructures (Agnew and Duygulu, 2005; Graff et al., 2007; Choi et al., 2009; Kabirian et al., 2015; Patra et al., 2014; Cyr et al., 2015), and both anisotropy and asymmetry can be predicted. However, the intensive computation costs strongly limit the applications of these approaches in practice. Thus, developing the constitutive formulations at the macroscopic level is the preferable way to achieve accurate and efficient simulation of complex forming processes (Lee and Barlat, 2014).

At the macro scale, regarding the yield criteria, flow rules and hardening laws, many continuum-based constitutive models have been proposed and numerically implemented into FE platforms (Banabic, 2010; Xiao et al., 2012; Lee and Barlat, 2014). To characterize the texture-induced anisotropy, as shown in Fig. 1, many anisotropic models have been proposed. To cover the 'abnormal' anisotropy of aluminum alloys, several anisotropic yield functions have been developed, extended and applied; the typical ones include Karafillis-Boyce model, YLD91, YLD96, YLD2000-2d, YLD2004-18p, Banabic model, the homogeneous polynomials (Karafillis and Boyce, 1993; Barlat et al., 1991, 1997, 2003, 2005; Banabic, 2010; Soare et al., 2008; Bron and Besson, 2004; Iadicola et al., 2008). In addition to the anisotropy, as shown in Fig. 1, asymmetry yield is observed for HCP structured materials and even BCC ones. The root cause is still under intensive exploration, but includes possibilities such as porosity deformation, the polar nature of twinning and non-Schmid law (Cazacu and Stewart, 2009; Bassani and Racherla, 2011; Mohr et al., 2013). Several efforts have been undertaken to describe the yield asymmetry aside from plastic anisotropy (Cazacu and Barlat, 2004; Cazacu et al., 2006, 2010; Plunkett et al., 2008; Cazacu and Stewart, 2009; Ghaffari et al., 2014; Tuninetti et al., 2015).

The above studies focus on describing the initial anisotropy or asymmetry behaviors for certain materials, and the evolution of the yield surface is largely described using combinations of isotropic and kinematic hardening laws (Wegener and Schlegel, 1996; Lee et al., 2008; Choi and Pan, 2009). Due to the interaction of multiple deformation mechanisms associated with complex microstructures, the distorted yielding and nonlinear hardening in full stress states during deformation have been frequently observed (Barlat et al., 2005; Choi et al., 2009; Khan et al., 2009). Within the Mises criterion framework, François (2001) introduced a 'distorted stress' to replace the usual stress deviator to obtain the 'egg-shaped' yield surface for an aluminum alloy used for both proportional and non-proportional tension-torsion loading paths. Taking combined isotropic, kinematic and distortional hardening into account, Shutov and Ihlemann (2012) proposed a rheological model to describe the distortion of the yield surface for an annealed aluminum alloy. By introducing three material parameters, a modified François model (2001) based on 'egg-shaped' subsequent yield surfaces has been developed to describe the change in the shape of the yield surface of the 1100 Al (Yue et al., 2014). Until now, modeling distorted plasticity and its evolution in full stress space still remains a challenge for practical metal forming.

This study focuses on accurately and efficiently modeling the distorted plasticity and its evolution of hard-to-deform materials for practical usage. First, we conduct a critical review of the methodologies for developing macroscopic

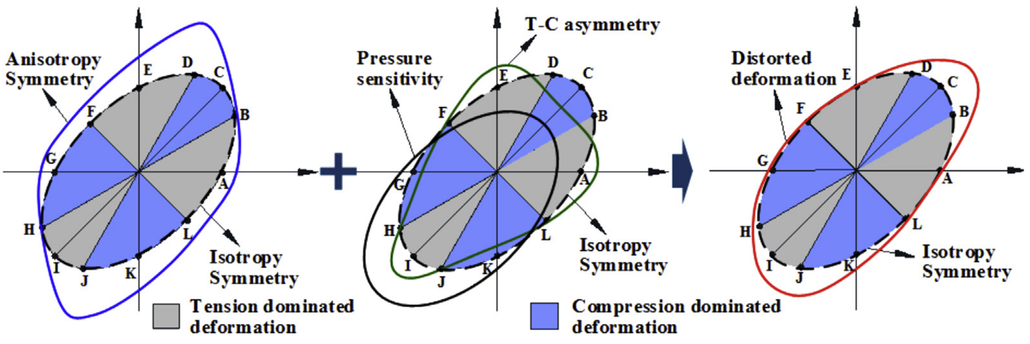

Fig. 1. Distorted behaviors induced by anisotropy and asymmetry.